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ANTENNA LABORATORY

Technical Report No. 29

MEASURING THE CAPACITANCE PER UNIT LENGTH OF BICONICAL STRUCTURES OF ARBITRARY CROSS SECTION

by

J. D. Dyson

Contract No. AF33(616)–3220
Project No. 6(7–4600) Task 40572
WRIGHT AIR DEVELOPMENT CENTER

JUN 1960

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A METHOD OF MEASURING THE CAPACITANCE PER UNIT LENGTH OF BICONICAL STRUCTURES OF ARBITRARY CROSS SECTION

SUMMARY

The characteristic impedance of an infinite length biconical structure, a lossless transmission line on which energy is propagated in the TEM mode, is simply related to the capacitance per unit length of the structure. This capacitance per unit length may be accurately measured by employing an extension of the conventional guard technique as used in the precise measurement of parallel plate capacitors.

An appropriate gap is cut in one of the arms of the line, converting the structure into a three terminal capacitor. If the arm beyond the gap is long enough, the desired field distribution will be maintained past the gap and the capacitance per unit length of the isolated or guarded section may be measured by conventional low frequency bridge techniques.

INTRODUCTION

The characteristic impedance of a structure such as the infinite length biconical transmission line is of interest when the line is terminated and operated as an antenna, since with increasing frequency the input impedance of the antenna may be expected to converge toward this characteristic value. A theoretical determination of this characteristic impedance for the coaxial biconical structure was presented by Schelkunoff[1] in 1941, and recently Carrel[2] has considered coaxial and non-coaxial biconical structures of arbitrary cross section, including the fin of zero thickness.

These structures have been shown to be, basically, lossless transmission lines which have a constant capacitance per unit length. Carrel has shown that for the TEM spherical wave the boundary value problem involved is reducible to a two-dimensional potential problem; he has then employed conjugate function theory to obtain the capacitance per unit length.

It is the purpose here to show how this capacitance per unit length can be accurately measured.

PRINCIPLE OF THE METHOD

The simple relationship between the characteristic impedance and the capacitance per unit length of a lossless uniform transmission line,

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(1) S.A. Schelkunoff, "Theory of Antennas of Arbitrary Size and Shape," Proc. IRE, Vol. 29, pp. 493-521, September 1941.

(2) R.L. Carrel, "The Characteristic Impedance of an Infinite Biconical Antenna of Arbitrary Cross Section," Accepted for publication in the IRE Transactions, PGAP.

immersed in a lossless medium, is well known[3] and has been used to obtain the characteristic impedance of coaxial and strip lines by relatively simple low frequency bridge measurements. In MKS units this relationship can be expressed as

$$Z_o = \frac{\sqrt{\mu \epsilon}}{3(10^8)\ C} \qquad (1)$$

where Z_o is the characteristic impedance in ohms, C is the capacitance per unit length in farads/meter, μ is the relative magnetic permeability, and ϵ is the relative dielectric constant of the medium.

For normal transmission lines one need only make the line of sufficient length to insure that the fringing capacitance at the end of the line is negligible compared to the total capacitance of the sample. However, if one attempts to measure the capacitance between the arms of the biconical line using the same procedure, it immediately becomes obvious that the end effect is a constant. The size of the arm end increases in proportion to the length of the arm.

A study of the distribution of the electric field around the biconical arms leads to the conclusion that this fringing capacitance can be controlled by resorting to an extension of the guard technique as used for the precise measurement of parallel plate capacitors and converting the biconical line into a three terminal capacitance. The guard-ring technique was introduced by Thomson in 1867[4] and the measurement of three terminal capacitances by low frequency bridge circuits has become well standarized,[5] so

(3) S.A. Schelkunoff, "Electromagnetic Waves," D. Van Nostrand Co., Inc., New York, Ch. 7, 1948.

(4) J.C. Maxwell, "A Treatise on Electricity and Magnetism," Vol. I, 1891, Republished by Dover Publications, Inc., New York, p. 331, 1954.

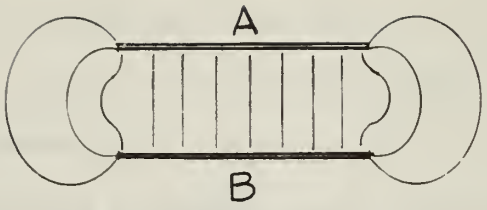
(5) M.B. Stout, "Basic Electrical Measurements," Prentice-Hall, Inc., Ch. 12, 1950.

it will be only briefly covered here in an effort to point out its application to the present problem.

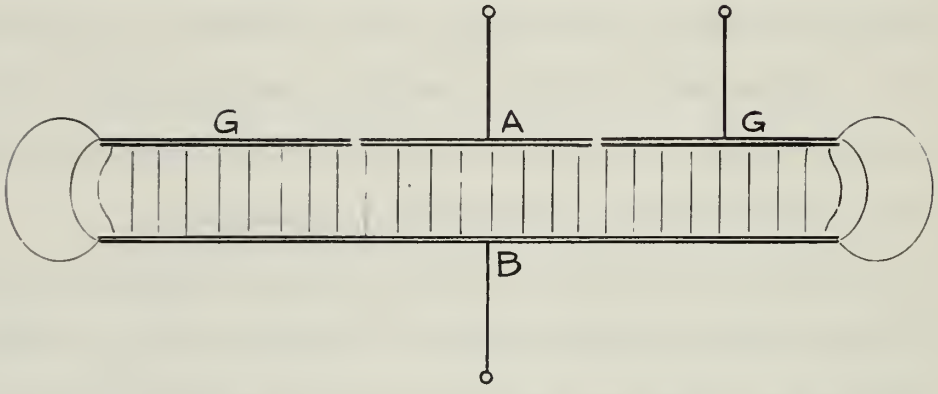
The guard ring is a special type of shield which is employed to measure parallel plate capacitors, which must be precisely calculable in terms of their dimensions, and of the dielectric constant of the medium between the plates. Figure 1 indicates the distribution of the electric field between the plates of a parallel plate capacitor with and without a guard ring. The plates are, for convenience, usually chosen to be circular and the guard consists of a ring lying in the same plane as the guarded electrode and separated from it by a narrow circular gap.

The distortion of the field between the plates caused by the field fringing at the edges can be eliminated by bringing the guard ring to the same potential as the guarded electrode. Under these circumstances the field between this electrode and an equivalent area of the bottom electrode remains essentially perpendicular to the plates. The desired capacitance C_{AB} can be isolated from the capacitances C_{AG} and C_{BG} by proper bridge techniques.

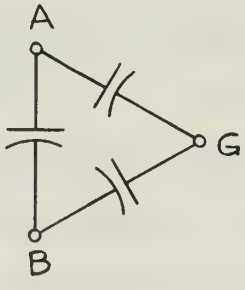
Figure 2 indicates how this technique can be applied to the biconical structures under consideration. Although the electric field lines now lie along a spherical surface, note that if a gap is cut in one arm sufficiently far from the end, and if at the moment of balancing the bridge the two arm segments A and G are brought to the same potential, the field lines will be undistorted beyond the gap. By the same bridge techniques employed with the normal parallel plate capacitor it is possible to isolate the capacitance between the guarded segment of the arm, segment A, and an equivalent area of arm B from the capacitances C_{BG} and C_{AG}. Thus it is possible to measure



(a) unguarded electrodes

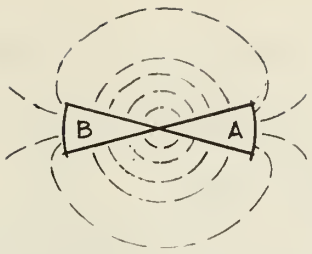


(b) guarded electrodes

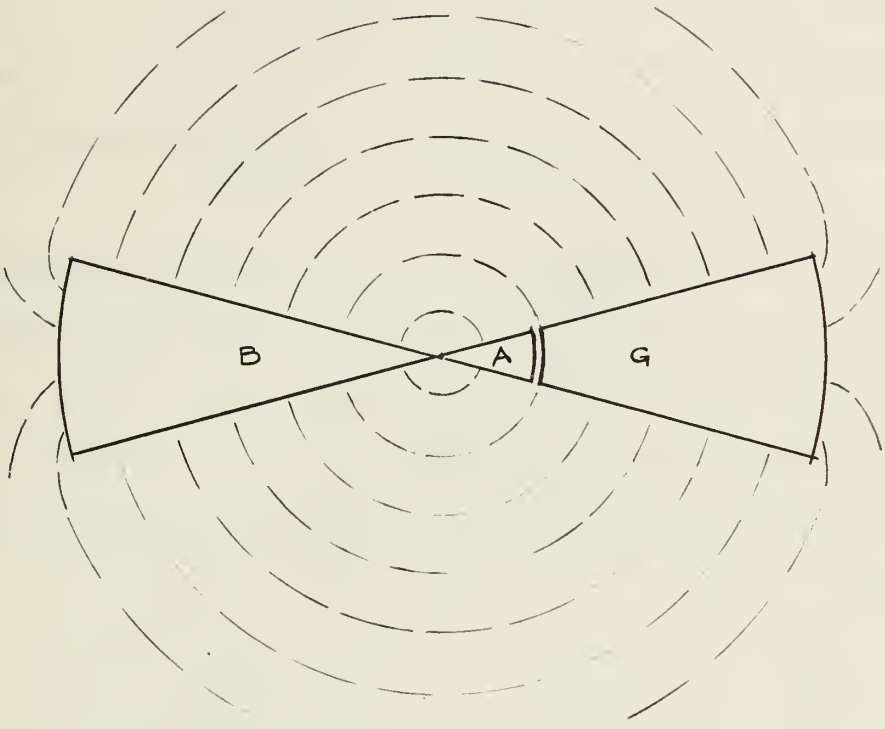


(c) equivalent circuit of b

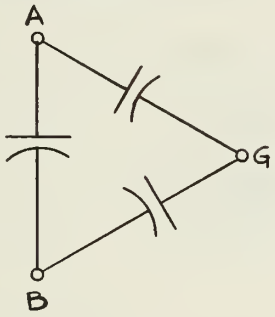
Figure 1. Approximate field distribution between guarded and unguarded parallel plane electrodes.



(a) unguarded arms



(b) guarded arms



(c) equivalent circuit of b

Figure 2. Guard technique applied to biconical structure.

the capacitance of this guarded length without fringing effects, and, from this, calculate a capacitance per unit length and the characteristic impedance of the structure.

This method of measuring the capacitance is applicable to all of the structures previously mentioned which are characterized by a constant capacitance per unit length. However, the measurements were confined to structures with fin shaped arms because of the availability of theoretical results for this structure as a result of Carrel's work, and because this type of line promised to provide the least constructional difficulties.

One interesting interpretation of this guarding technique is to consider the guard arm, "G", as providing a proper termination for the line composed of arm "A" and its equivalent area on arm "B". The unguarded antenna, then, is analogous to an open circuited transmission line and the guarded antenna to a line terminated in its characteristic impedance.

THE EXPERIMENTAL EQUIPMENT

It is possible to measure the direct capacitance between two terminals of a three-terminal network if a fifth point is added to the conventional four-arm bridge network, as shown in Figure 3.[6] This network is in balance if either of the following conditions is fulfilled.

$$\frac{K}{N} = \frac{L}{P} = \frac{F}{H}$$

$$\frac{K}{L} = \frac{N}{P} = \frac{S}{T} . \qquad (2)$$

(6) R.F. Field, "A Guard Circuit for Capacitance Bridge Measurements," General Radio Experimenter, March 1940.

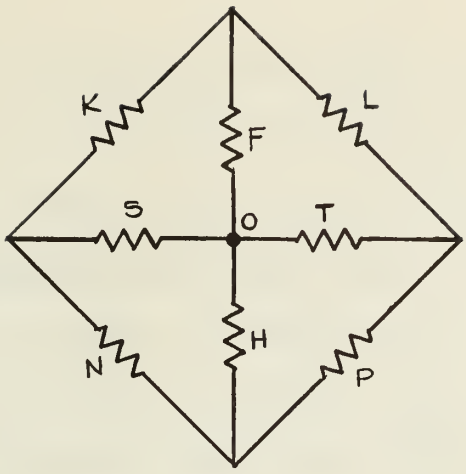


Figure 3. Five-terminal bridge

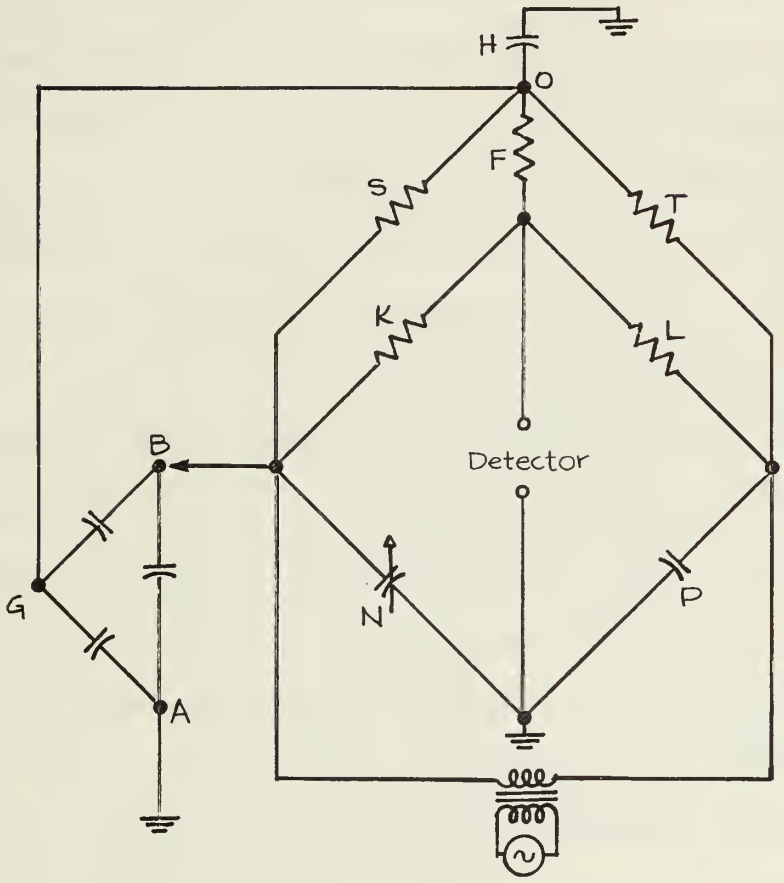


Figure 4. Simplified schematic of bridge and unknown capacitor.

Fundamentally the circuit can be considered to be a main bridge composed of elements K, L, N, and P and an auxiliary bridge (or guard circuit) formed by elements S, T, N and P, where F and H are coupling elements between the bridges. The bridge is balanced by connecting point "O" to the junction N-P, placing element S in parallel with N, and T in parallel with P. Successive balancing of the main bridge alone and the bridge with these elements paralleled will satisfy the conditions of equation (2). Similarly the bridge is balanced alone and with "O" connected to the junction K-N. For measurement purposes the unknown capacitance C_{AB} may be placed across the bridge element N and the capacitances C_{AG} and C_{BG} across elements H and S, respectively, as in Figure 4. Thus we see that the desired capacitance, C_{AB}, is placed in the main bridge and the other two capacitances of the three terminal capacitance are placed in the auxiliary bridge or across one of the coupling elements.

Figure 4 is a very much simplified schematic of the connections between the bridge and unknown capacitor. Figures 5 and 6 show the complete bridge schematic and the necessary shielding arrangements. The bridge as constructed uses a substitution method of measurement whereby the main bridge is balanced by adjusting element N with the unknown terminal B disconnected. Terminal B is then connected and element N varied to rebalance the bridge. This bridge element was a calibrated General Radio No. 722D air condenser. Fundamentally, the accuracy of the capacitance measurement is limited by the accuracy of calibration of this standard.

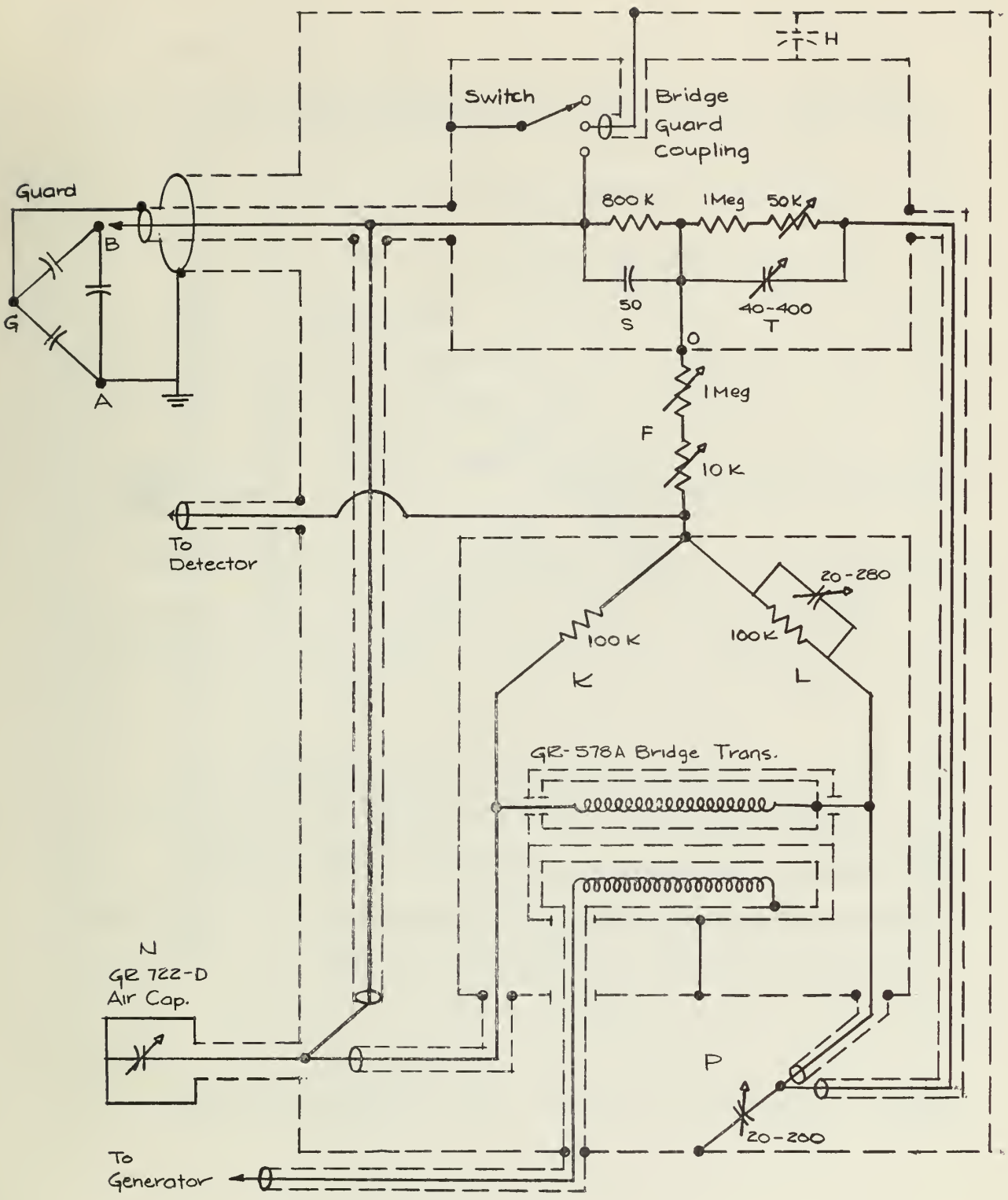


Figure 5. Schematic diagram and shielding of bridge and guard.

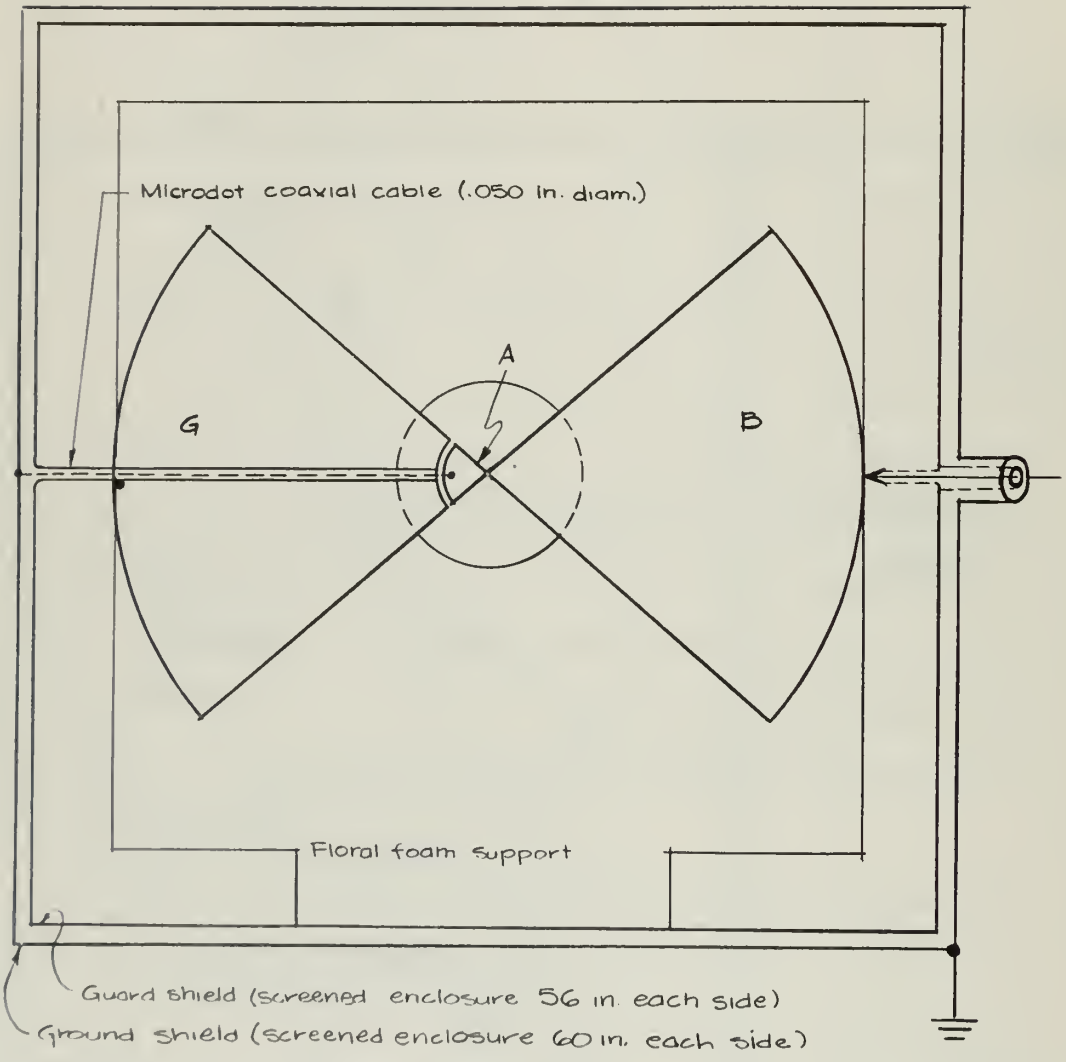

Microdot coaxial cable (.050 in. diam.)
A
G
B
Floral foam support
Guard shield (screened enclosure 56 in. each side)
Ground shield (screened enclosure 60 in. each side)

Figure 6. Biconical line mounted in double shielded enclosure.

It should be noted that, in a measurement of this type, proper shielding of the bridge components (from each other and from external objects) and of the biconical arms is of the utmost importance. The capacitance between the arms is of the order of a few micromicrofarads and the stray capacitance between the arms and surrounding objects may be as large or larger. Therefore, all capacitances must be carefully controlled and placed across appropriate arms of the bridge--the desired capacitance across the main bridge and all stray capacitances, including those between the bridge arms themselves, across auxiliary arms or otherwise taken into account.

Complete shielding from all external fields is, of course, necessary if a complete null is to be obtained. Figure 7 is a block diagram of the measurement setup, including the 1000 cycle source and detecting equipment.

It should be mentioned that the bridge as constructed is equivalent to a combination of the General Radio Type 716-C capacitance bridge and Type 716-P4 guard circuit. In fact, this combination or the Leeds and Northrop shielded capacitance bridge would have admirably served the purpose but unfortunately were not available when these measurements were made. The reader is referred to reference 6 and to the instruction manual for the GR 716-P4 guard circuit for an excellent discussion of the measurement techniques.

THE EXPERIMENTAL TECHNIQUE

To check the accuracy of the equipment a guarded parallel plate

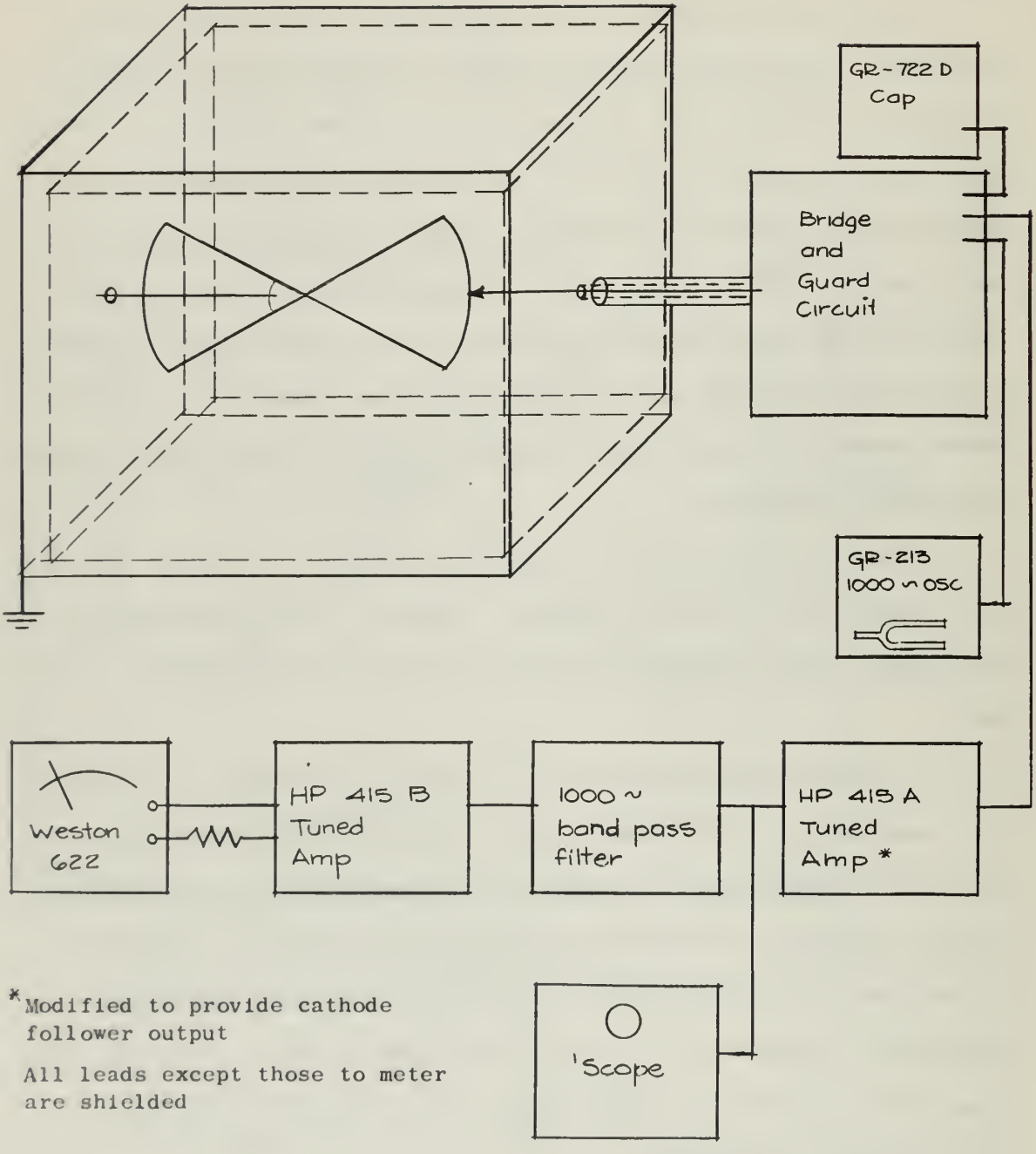


Figure 7. Block diagram of equipment

capacitor was constructed, with all critical dimensions held to $\pm$ .001 inch. Air dielectric was used and the calculated capacitance of 0.94 $\mu\mu$f could be repeatedly measured within $\pm$ 1%.

The coplanar arms of the fin lines measured were constructed of .015 inch cold rolled copper supported by a two inch thick sheet of "Floralfoam." This foam material was cut away from the guarded portion of the arms, as indicated in Figure 6.

The placement of the leads connecting the three portions of the line to the bridge proved to be quite critical. A study of the fields surrounding the line and the effect of these leads on the measured results led to the conclusion that the leads to portion B and G should extend along the axis of the structure to the proper terminal on the shielding enclosure, as shown in Figure 6. The placement of the lead to portion A was solved by shielding it completely from arm B. The lead to G is the outer shield of a "Microdot" coaxial line, .050 inch in diameter. This line was then continued along the surface of arm G up to the gap where the center conductor was exposed, to bridge the gap and connect to arm A. The relatively high capacitance of the cable appears as a part of capacitance C_{AG} and does not become a part of the desired capacitance C_{AB}. It is, of course, obvious that the leads cannot be made invisible and that they do disturb the fields. This placement effectively confines the distortion to the fields between electrodes B and G, and hence alters only capacitance C_{BG}.

The total arm length was initially constructed to be 24 inches; however, this was later reduced to 21 inches to increase the separation between the arms and the shielding enclosure. The guarded portion was

varied in length to determine the effect of the guard. It was determined that as long as the guarded portion was approximately 4% or less of the total arm length the capacitance per unit length appeared constant, indicating a normal distribution of the electric field in this area. As the ratio of guarded to total arm length became greater, the effectiveness of the guard began to decrease.

A guarded arm length of one and one half inches was decided upon as providing sufficient capacity to be accurately measured and still be adequately guarded. The length of the guard arm that could be used was limited by the size of the shielding enclosure. The gap between the guarded arm, "A" and the guard arm, "G", was maintained at .020 inch, the width of a saw cut, using a jeweler's blade in a scroll saw.

Before any measurements were taken the equipment was allowed to stabilize for a minimum of two hours. All capacitance measurements were repeated at least three times. These readings were averaged to provide a total capacitance reading which was divided by 1.5 to obtain a value of the capacitance per inch of arm. This procedure was repeated for lines of half angular width from 15 to 85 degrees.

RESULTS

The measured capacitance per unit length of the infinite length balanced fin line is shown in Figure 8. The measured values agree within one percent with the values calculated from Carrel's work for arms with Ψ ranging from 30 to 75 degrees and within two percent for a half angle width 85 degrees. However, the measured value has diverged from the theoretical value by approximately nine percent for a half angle of 15

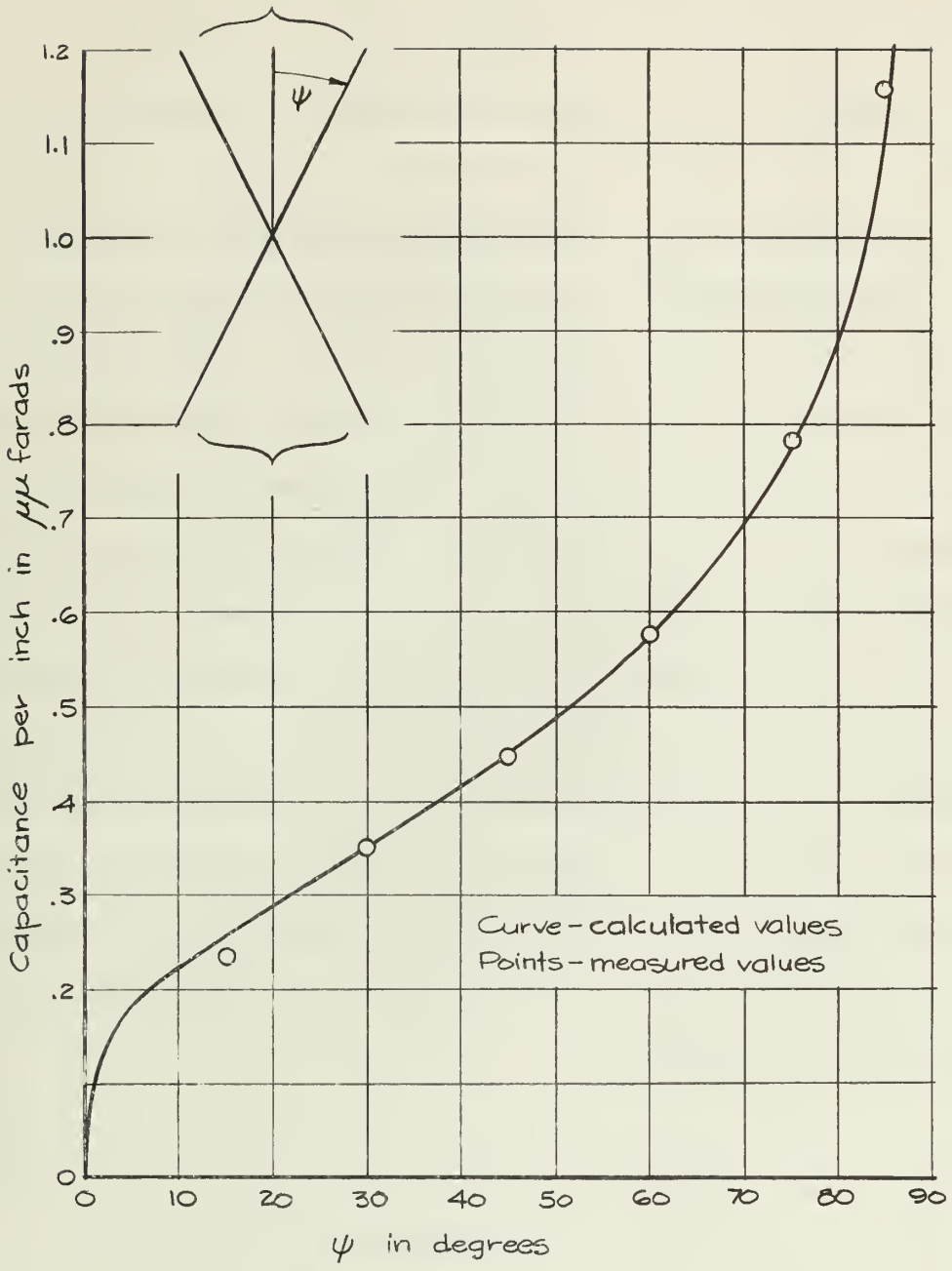


Figure 8. Capacitance per unit length of infinite length balanced fin as a function of angular arm width (calculated values after Carrel)

degrees. This was traceable to a loss in the effectiveness of the guard as the arm became narrow. A longer guard arm, and consequently a larger shielded enclosure, should increase the accuracy of measurement in this region.

It is recognized that two obvious factors have contributed to the error in the measurements: (1) The fin line, although only .015 inch in thickness, was not a zero thickness structure. While this might be insignificant to the fields away from the origin, this thickness becomes increasingly important as the origin is approached and the antenna width approaches zero. (2) The line was not suspended entirely in free space although a minimum of dielectric was placed in the most critical part of the field. In this connection the dielectric constant of the Floralfoam dielectric used was measured, using a parallel plate capacitor and the bridge setup itself, and the measured value of 1.02 agrees with published data of the manufacturer. It may be possible to eliminate or reduce these sources of error for other types of structures and thereby increase the accuracy of measurement. In addition, a commercial bridge of greater accuracy could be employed.

CONCLUSIONS

The extension of the parallel plate guard technique to structures such as the biconical transmission line has been demonstrated to be practical. This provides an accurate method of measuring the capacitance per unit length of this type of antenna structure. An application of the technique to the balanced fin transmission line provided measured results which were in good agreement with calculated values.

ACKNOWLEDGEMENT

The author is pleased to acknowledge several very helpful discussions with W.L. Weeks of the Antenna Laboratory of the University of Illinois and the assistance of R.L. Jones of the laboratory, who performed most of the measurements.

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